ANALYTICAL MODEL FOR ASSESSING THE RESILIENCE OF CROSS-BORDER CRITICAL TRANSPORTATION INFRASTRUCTURE

FABIO BORGHETTI & GIOVANNA MARCHIONNI
Mobility and Transport Laboratory, Politecnico di Milano, Italy

ABSTRACT

Modern industrialized countries depend on the proper functioning of interdependent infrastructure systems, such as transportation, energy, water, and telecommunications networks. These systems are often critical because they contribute to the organization, functionality, and stability of society. Accidents and disruptions can affect these systems, generating consequences and impacts on the economy, health, safety, and welfare of citizens in one country or several neighboring countries. In case of disruption of a critical cross-border transportation infrastructure, impacts affect not only the area of the event but also a wider area. Depending on the type of event and estimated duration, impacts on the mobility of people and goods can be assessed by considering delays, increased traffic, and potential increase in accidents. The goal of this paper is to present an analytical model to study the resilience of critical road and rail transportation infrastructure; the model is applied to a case study including the Lombardy region (Italy) and Canton Ticino (Switzerland) to verify its validity. The proposed model was developed within the SICt project – Resilience of Cross-Border Critical Infrastructure as part of the Interreg VA Italy–Switzerland Program 2014–2020. The model proposes a resilience index (*RI*) calculated for the road and rail transport network element (link). The formulation of the index considers three independent indicators: (i) *RIRM* (resilience index – rescue management) related to the resources that can be activated and used to cope with an event; (ii) *RIPP* (resilience index – plans and management) related to the rapidity with which the necessary resources can be activated considering the presence of plans and procedures; and (iii) *RIRN* (resilience index – network and traffic) related to the robustness of the transport network elements. This paper focuses on the third indicator (*RIRN*) with reference to the analytical formulation and application of the case study.
Keywords: transport resilience, critical infrastructures resilience, critical infrastructures safety, emergency management, transport vulnerability, road network.

1 INTRODUCTION

Modern, industrialized societies are increasingly dependent on the functioning of interdependent systems and infrastructures, such as information technology, transportation (e.g., road, rail, air and sea), energy and water networks. Dependence is when there is a link or connection between two infrastructures and the state of one infrastructure influences or is related to the state of the other. Interdependence consists of a bidirectional relationship between two infrastructures through which the state of each influences or it is related to the state of the other [1]. These systems and infrastructures are often considered critical because they are necessary for the organization, functioning and stability of a country [2], [3]. Failures, malfunctions, and more generally relevant events of anthropogenic or natural origin make these systems vulnerable, generating consequences for the economy, health, safety, and well-being of the citizens of an entire country or of several neighboring countries [4], [5]. The disruption of a critical transportation infrastructure, road or rail, can have effects not only at the location of the event, but also on a wider area. Depending on the type of event, which can be natural (e.g., landslide, flood, earthquake, etc.) or anthropogenic (e.g., road accident) in origin, and its relative duration, it is possible to estimate the impacts on the mobility of people and goods. Impacts can be analyzed by considering, for instance, delays (alternative

WIT Transactions on The Built Environment, Vol 214, © 2022 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/SSR220071

routes), increased traffic (congestion), and possible increase in accidents. More generally, socioeconomic impacts on the community can be estimated. At the European level, the Trans-European Network Transport (TEN-T) has been defined as the set of linear (rail, road and river) and punctual (urban nodes, ports, interports and airports) infrastructure considered important at the community level. In practice, nine strategic corridors were identified with the goal of promoting coordinated implementation and development of the Trans-European Transport Network among different states. In addition, European Directive 2008/114/EC on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection was released in 2008; in particular, the energy and transport sectors are considered. To date, an update of the Directive is underway. With this in mind, the aim of this research is to propose and to apply a quantitative method to characterize the links of a road or of a rail transportation network according to a resilience index (RI). This index is composed of three indicators: (i) *RIRM* – rescue management related to the resources that can be activated and used to cope with an event; (ii) *RIPP* – plans and management related to the speed with which the necessary resources can be activated and, in fact, considers management aspects such as the presence of plans and procedures; (iii) *RIRN* – network and traffic related to the robustness of the elements of the transportation network. In this paper, the third *RIRN* indicator is illustrated along with an application case. The paper is organized as follows: Section 2 provides the background with reference to the technical and scientific literature on the issues of vulnerability and resilience; Section 3 illustrates the method from an analytical point of view while Section 4 deals with the application of the method in the Interreg IT-CH SICt project; finally, Section 5 contains the conclusions.

2 BACKGROUND

The topic of vulnerability and resilience of transportation networks is continuously addressed by various authors in technical scientific literature. Definitions of vulnerability and resilience are proposed in the several studies, but to date it is almost impossible to define them in a unique way. However, over the years the scientific community has managed to consolidate some important issues. When discussing critical transportation infrastructure and more generally systems for the mobility of people and goods, it is necessary to define their vulnerability according to potential risks. In this way, decision-making processes that support intervention strategies and policies can be identified and undertaken [6]. More generally, risk can be estimated by considering the probability of occurrence of a specific hazard, identifying the affected elements and assessing their vulnerability to that specific hazard [7], [8]. As a matter of fact, vulnerability is considered an element of risk along with probability and exposure [9]. Making a focus on the transportation sector, vulnerability can be defined as the susceptibility to incidents that may result in significant reductions in road network operations [10], [11]. Vulnerability can also be studied by considering different components: physical, functional, organizational, systemic, and topological [12]. The concept of resilience is addressed by scholars on network systems such as energy, transportation, water and communications [11], [13]. Again, it is difficult to provide an unambiguous definition; however, the term resilience comes from the Latin resilĭens-ĕntis, the present participle of resilīre meaning to bounce, to jump back. It may also be interesting to connect it with the Latin meaning of resalio, which describes the act of getting back on the boat overturned by the force of the sea: this interpretation is used in the psychological field to indicate the attitude of going forward without giving up, despite difficulties. Among several definitions acknowledged by the scientific community, resilience can be defined as the ability of a system to withstand a major disruption within acceptable degradation parameters and to recover within acceptable time and cost and compound risks [14], [15]. A system, including one related to transportation and mobility, can be considered resilient if it is characterized by a reduction in (i) the probability of failure/malfunction; (ii) the consequences of failure, considering, for example, loss of life, damage, and economic and social consequences; and (iii) recovery time [16], [17]. Basically, resilience can be defined as the ability of an entity and/or system to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance and more generally from an event. Fig. 1 shows the operational state (performance) of a transportation system as a function of time, considering a relevant event (red point). The trend of the blue curve represents the evolution of system performance over time following the relevant event and can be a useful tool to support traffic, mobility and emergency management. In addition, the different elements that make up resilience are illustrated.

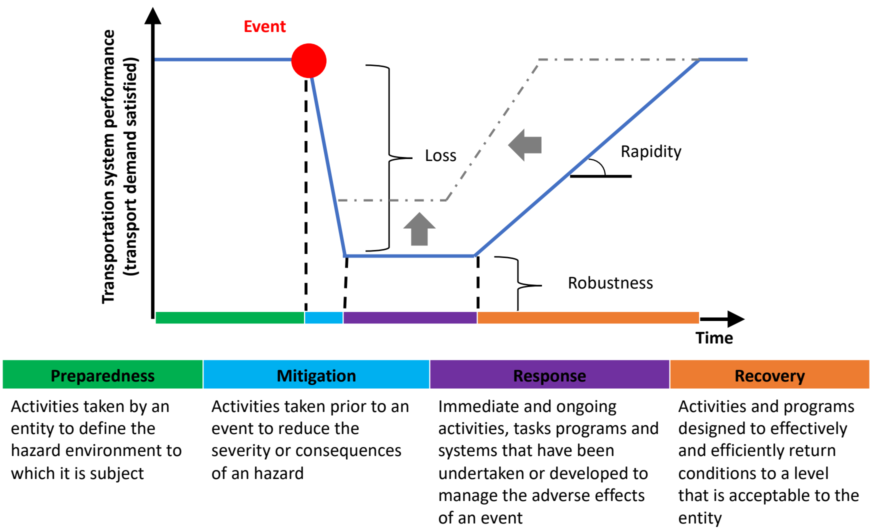


Figure 1: Resilience components for a transport system. *(Source: Adapted from [17], [18].)*

With reference to the management of traffic and mobility of people and goods, it is also important to consider the availability, practicability, and redundancy of routes, which can offer alternatives in the event of a disruption of an element (link). The system can be highly resilient not only if it can resist an event, but also if there are shared procedures and plans for traffic and emergency management. For the management of emergencies following relevant events, it is essential to consider the availability of resources (vehicles, equipment, etc.) that can be activated and used by analyzing, on the one hand, the accessibility of rescue at the location where the event occurred (intervention time) and, on the other hand, redundancy, i.e., how many resources of the same type can be used in the unit of time [12].

3 MODEL DESCRIPTION

A resilience index (*RI*)is calculated for each link *i* of the road and rail transportation network; the Index describes the capacity of each link to cope with a relevant event, whether anthropogenic or natural. *RI* is composed of three independent indicators (see Fig. 2):

$$RI_i = f(RIRM_i; RIPP_i; RIRN_i) \tag{1}$$

where:

- *RIRM* aggregates resilience indices related to the resources that can be managed to cope with a relevant event;
- *RIPP* considers how quickly resources can be activated and managed by assessing the presence, the sharing, and the application of plans and procedures;
- *RIRN* considers the robustness and the importance of network elements based on their relationship to the whole network.

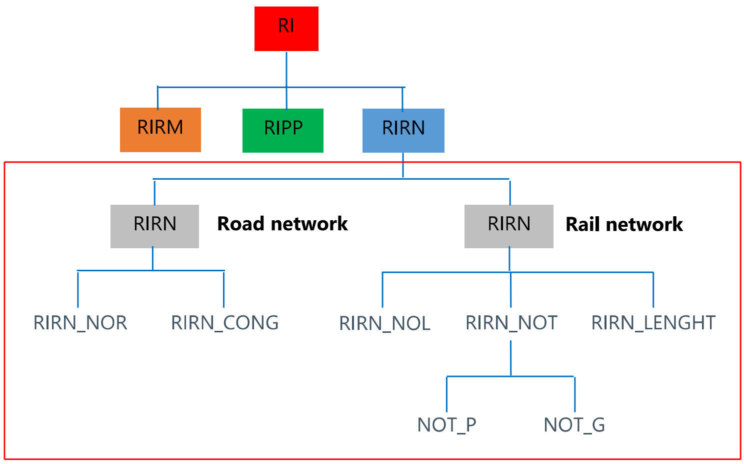


Figure 2: Resilience index analytical structure and focus on the *RIRN*.

The third indicator *RIRN* – network and traffic resilience index, considers the interaction between individual network elements (links) and the network itself both road and rail. In practice, the goal is to assess how important a link is in relation to the entire network if it is not viable following a relevant event. From an analytical point of view, the indicator is calculated differently for the road and rail network. For the road network, the two attributes are considered as follows:

$$RIRN = \mu_1 * RIRN\_NOR + \mu_2 * RIRN\_CONG \quad (2)$$

where:

- *RIRN_NOR* is the number of routes that affect a single link in the road network;
- *RIRN_CONG* represents the traffic/congestion level of the individual road link;
- $\mu 1$ and $\mu 2$ are the relative importance weights of the two indicators. The flexibility of the model allows the analyst to vary the weight and thus the importance of the two contributions.

For the rail network, the three attributes are considered as follows:

$$RIRN = \mu_1 * RIRN\_NOL + \mu_{2rl} * RIRN\_NOT + \mu_{3rl} * RIRN\_LENGTH \quad (3)$$

where:

- *RIRN_NOL* is the number of lines affecting a single link in the rail network;

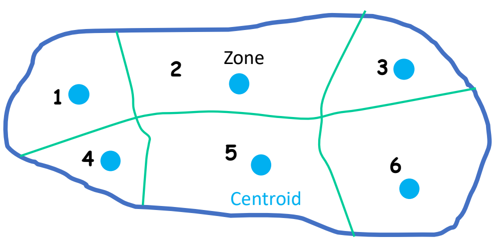
- *RIRN_NOT* represents the number of trains in the individual rail link;
- *RIRN_LENGTH* represents the relationship between a link and the length of the railway line;
- *μ1, μ2* and *μ3* are the relative importance weights of the two indicators. Again, the flexibility of the model allows the analyst to vary the weight and thus the importance of the two contributions.

3.1 Road network

3.1.1 Calculation of the attribute *RIRN_NOR*

This attribute provides information regarding the number of routes that pass an on single link in the transportation network. Regarding the road network, routes are defined as a sequence of links in the network that join origin–destination (OD) pairs. The calculation of this indicator involves on the one hand zoning the territory (study area) and on the other hand analyzing the routes joining the different OD pairs.

Zoning allows the study of transportation demand: the area is divided into zones and for each zone a centroid is identified that ideally represents the starting and/or ending point of journeys. Zoning is generally the result of a trade-off between quality of analysis and computational burden and still depends on the level of analysis (scale) to be performed; choosing to use smaller zones increases the accuracy of the calculation but also increases the computational burden as there will be more OD pairs to consider. Otherwise, when larger zone sizes are used, the accuracy of the analysis decreases and the computational burden is also reduced. The zoning phase allows the implementation of the OD matrix that in fact represents the transportation demand between each OD pair as illustrated in Fig. 3. Starting from an area (blue line in Fig. 3) it is possible to define zones to which a centroid (blue dot) can be associated. In the example, six zones have been defined, allowing the study of transportation demand (e.g., number of trips, number of passengers, number of vehicles, etc.) using the OD matrix. If the same area had been divided into a larger number of zones, the accuracy would have increased along with the computational burden.



Origin/ Destination	1	2	3	4	5	6
1						
2						
3						
4						
5						
6						

Figure 3: Example of zoning a territory (six zones and six centroids) and OD matrix.

Also, by way of example, it is possible to consider an area divided into four zones as shown in Fig. 4. The blue dots represent the centroids of a zone; the black dots are the nodes and the black arrows are the (oriented) links of the transport network. In fact, the network consists of four nodes (10, 11, 12 and 13) and five links (10–11, 10–12, 11–13, 10–13 and 12–13).

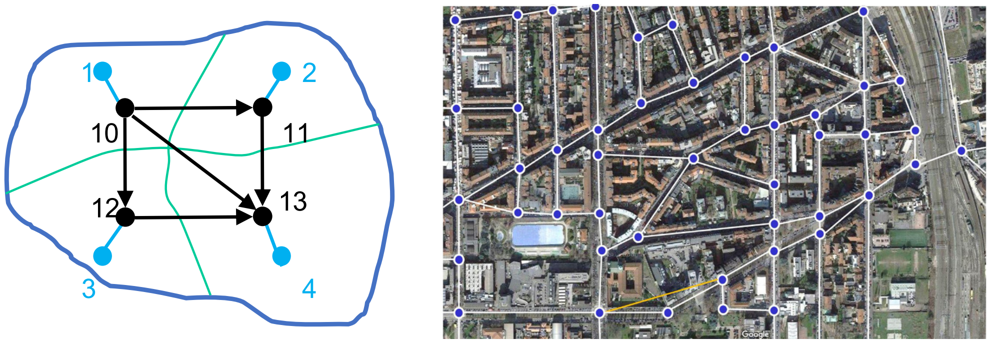


Figure 4: On the left example of four-zone zoning and representation of the transportation network consisting of links and nodes; on the right real example of representation of the transportation network consisting of links and nodes.

With reference to the example in Fig. 4, it is possible to identify seven routes connecting the four zones – OD as shown in Fig. 5. The routes are identified as the paths characterized by the lowest cost to the user considering travel time as the cost.

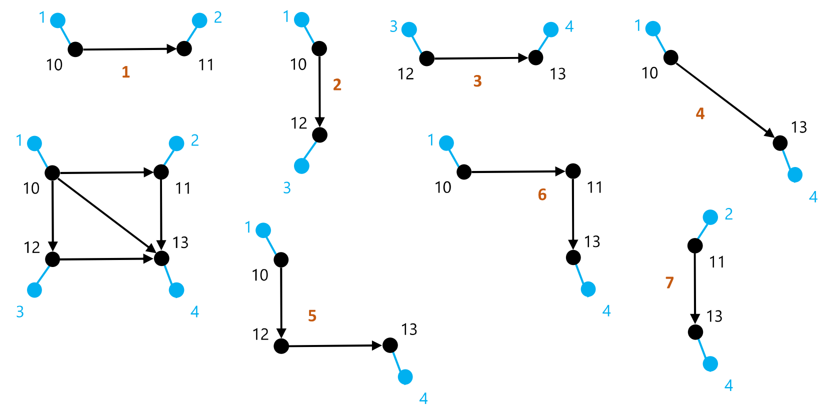


Figure 5: Identification of the seven paths connecting the four OD zones.

In this way it is possible to implement the links–routes incidence matrix where the rows show the links that compose the transportation network (in the example five links) and the columns show the previously identified routes (seven routes) as shown in Fig. 6. For each route the sequence of the links–routes is shown. The values allowed in the matrix are “1” if the link belongs to the generic route or “0” if otherwise.

With this approach, it is possible to know for each link how many paths pass through it; for example, link 12–13 is affected by two paths (3 and 5) while link 10–13 is affected by only one path (4). The next step is to normalize the *RIRN_NOR* attribute using utility functions with a stepwise trend as shown in Fig. 7. On the horizontal axis is the number of paths in each link in the network (*r1, r2, r3, r4*, and *r5*), while on the vertical axis is the normalized value. Five intervals giving rise to five values of the attribute were defined.

Routes

Links

A =

	1	2	3	4	5	6	7
	1-10-11-2	1-10-12-3	1-10-11-2	1-10-13-4	1-10-12-13-4	1-10-11-13-4	2-11-13-4
10-11	1	0	0	0	0	1	0
10-12	0	1	0	0	1	0	0
12-13	0	0	1	0	1	0	0
10-13	0	0	0	1	0	0	0
11-13	0	0	0	0	0	1	1

Figure 6: Example of links–routes incidence matrix.

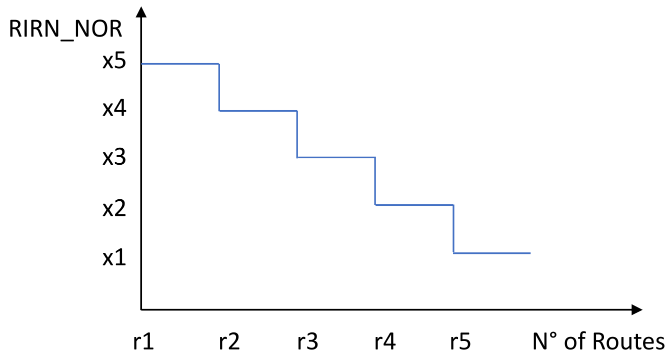


Figure 7: Utility function trend for the calculation of the *RIRN_NOR* attribute.

For instance, the *i*-th link in the transport network may be characterized by a high value of *RIRN_NOR* (x5) because the number of paths passing through it is limited (*r1*); instead, a link characterized by a high number of paths passing through it (*r5*) will be marked by a low value of *RIRN_NOR* (*x1*). In practice, it is reasonable to assume that a link affected by many routes is less resilient because in the event of a disruption, there will be effects and impacts on a larger number of OD pairs; this means that the disruption of the link will have a relevant effect on the network because it will impact on many areas by not guaranteeing connectivity and thus the mobility of people and goods.

3.1.2 Calculation of the attribute *RIRN_CONG*

The second attribute concerns the traffic flow/congestion level of the individual link in the road transport network. If a link has a high level of traffic and/or congestion, it is reasonable to assume that it is an important element in ensuring the mobility of people and goods on the network. In fact, this second attribute can be considered complementary to the previous one concerning the number of routes that affect a link. With reference to the example in Fig. 8 there can be situations where the link (21–24) of the network can be characterized by many routes (four) with low traffic flows (left) or situations where a link is characterized by only one route but with high traffic flows (right). Then there are intermediate situations depending on the configuration of the transportation network.

To consider these two issues simultaneously, the second attribute allows one to assess the presence of high traffic flows or congestion on a single link in the road network. Specifically, the travel time of a link under normal conditions (*Ttrav*) and the travel time during peak hour,

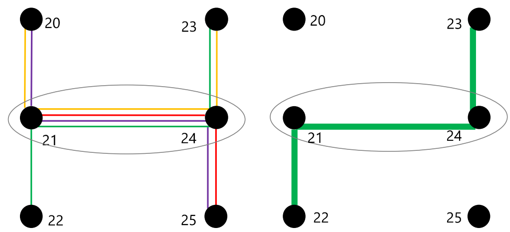


Figure 8: Example of link (21–24) affected by many routes but with limited traffic flow (left) and link affected by only one route characterized by high traffic flow (right).

when the highest traffic flow and possible congestion is assumed (*Tpeak*) are considered. The next step is to determine for each link of the road network the parameter *k* as follows:

$$k = \frac{T_{peak}}{T_{trav}} \quad (4)$$

If the *k* value is very high, the link is very congested; on the other hand, if it is equal to 1, it means that during the peak hour the traffic level is not relevant. Again, normalization of the *RIRN_CONG* attribute is performed using utility functions with a stepwise trend as shown in Fig. 7. In practice, it is reasonable to assume that a link affected by a high level of traffic and/or congestion (k >>1) is less resilient since in the event of disruption it will be necessary to manage many vehicles (light and heavy) by taking specific measures such as using viable alternative routes and/or blocking heavy vehicles, etc.

3.2 Rail network

3.2.1 Calculation of the attribute *RIRN_NOL*

This attribute provides information regarding the number of rail lines that pass over a single link in the transportation network. Unlike the road case where the study area has been zoned, it is necessary to consider the geometry of the network and the service provided. For each rail link, it is then possible to determine the number of lines that pass through it. It follows that a link characterized by many lines can be considered less resilient since in the event of disruption it will cause many origins and destinations to be disconnected; this means that the disruption of the link will have a major effect on the network because it will impact many areas by not guaranteeing connectivity and therefore the mobility of people and goods. The next step is to normalize the value of the *RIRN_NOL* attribute using utility functions with a stepwise trend as shown in Fig. 7.

3.2.2 Calculation of the attribute *RIRN_NOT*

The second attribute refers to rail traffic and specifically to the number of trains passing through the individual link in the rail network. Similar to the approach taken for the road network, if a link has a large number of trains, it is reasonable to assume that it is an important element in ensuring the mobility of people and goods on the entire transport network. Again, the attribute can be considered complementary to the previous one concerning the number of lines that affect a link; there may be situations in which a link in the rail network may be characterized by many lines with a reduced number of trains or situations in which a link is characterized by only one line but with a high number of trains. Then there are intermediate situations depending on the configuration of the transportation network. Since in general, the rail network can be used by both passenger and freight trains, the attribute is calculated as follows:

$$NOT \quad = \eta_1 * NOT\_P \quad + \eta_2 * NOT\_G \tag{5}$$

where:

- *NOT* is the number of trains affecting a single link in the rail network;
- *NOT_P* represents the number of passenger service trains affecting a rail link;
- *NOT_G* represents the number of cargo trains affecting a rail link;
- $\eta 1$ and $\eta 2$ are the relative importance weights of the two parameters. Again, the flexibility of the model allows the analyst to vary the weights and thus the importance of the two contributions.

As in the previous cases, it is necessary to normalize the value of the *RIRN_NOT* attribute using utility functions with a stepwise trend as shown in Fig. 6. Again, it is reasonable to assume that a link affected by many trains is less resilient because in the event of a disruption it will be necessary to handle many trains (passenger and freight) by adopting specific measures planned by the service operator (e.g., bus bridging for passenger service).

3.2.3 Calculation of the attribute *RIRN_LENGTH*

The third attribute concerns the relationship between the railroad link on which the relevant event is assumed and the length of the line. The longer a line is, the more reasonable it is to assume that the disruption of the link belonging to the line will cause impacts and consequences on the entire rail network. In fact, longer lines are desired to be penalized, which, in the event of link disruption due to an event, may suffer delays and consequences even over long distances. Again, it is necessary to normalize the value of the *RIRN_LENGTH* attribute using utility functions with a stepwise trend as shown in Fig. 7.

4 CASE STUDY: THE INTERREG SICT PROJECT

The SICt – Resilience of Cross-Border Critical Infrastructure project is developed under the Interreg V-A Italy–Switzerland 2014–2020 cooperation program that contributes to the goals of the Europe 2020 strategy. The project area includes the Lombardy Region in Italy and the Ticino Canton in Switzerland, as illustrated in Fig. 9 and is organized into six work packages (WP). The main goal of the project is to increase knowledge and information sharing on critical cross-border infrastructure with reference to transport infrastructure. These infrastructures represent important and strategic corridors for the mobility of people and goods also at the European level. Three specific goals have been identified for the implementation of the project: (i) to increase and improve cross-border cooperation in terms of governance to manage anthropogenic and natural events that may affect critical infrastructure (road and rail); (ii) to strengthen joint capacities for managing the impacts caused by disruption of cross-border critical infrastructure that may cause effects on both countries (emergency and traffic management); and (iii) to verify and to improve the effectiveness of the cooperation system for monitoring and managing relevant events in the cross-border area (macro-regional area).

Events affecting road and rail transportation infrastructure are considered in the study area; impacts of events occurring within the study area are evaluated in the impact area (see Fig. 10). Some representative results of *RIRN* related to the road and rail network are shown in Fig. 11. Links in green color have a higher indicator value than those in black color; therefore, they are found to be more resilient.

Figure 9: Main information and area of the Interreg SICt project.

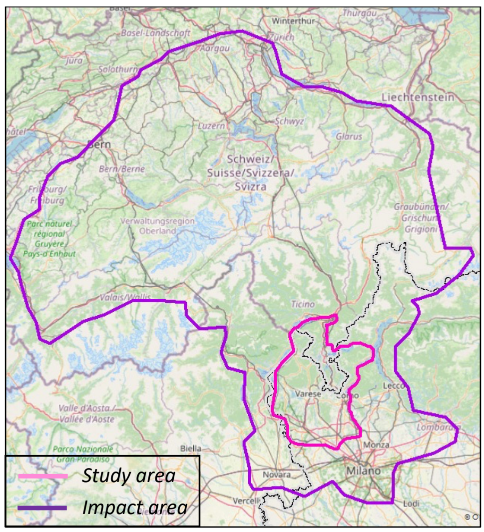


Figure 10: Study area and impact area of the Interreg SICt Project.

5 CONCLUSION

The paper presents the analytical formulation and application of a Resilience Index (*RI*), determined for each element of the road and rail network. The proposed approach can be considered as a useful decision support system (DSS) that can be used by those involved in the decision-making process of planning and managing the resilience of transportation infrastructure (infrastructure managers, first responders, administrations, etc.).

The method can be used in two phases: (i) planning phase, when it is necessary to simulate the joint response of the usable and available resources and each operator can share and know the critical points of the transportation network; (ii) emergency phase, to provide stakeholders

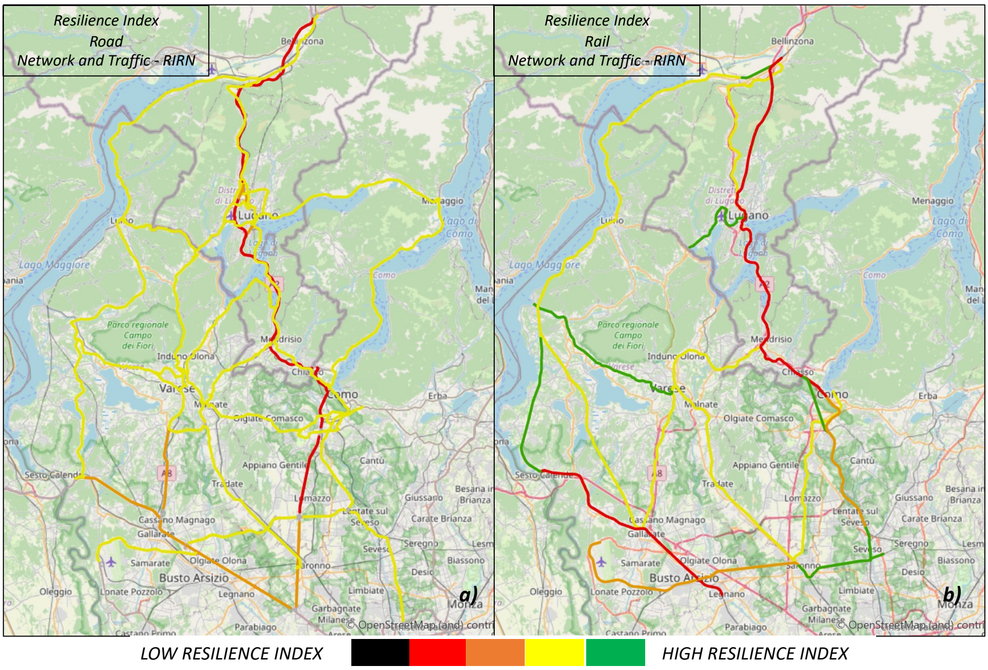


Figure 11: (a) *RIRN* of the road network; and (b) *RIRN* of the rail network.

with an assessment of the impact of the event on the network based on the available resources and the condition of the network itself. By comparing the different links that make up the transportation network, it is possible to prioritize interventions, identifying situations where it is most urgent to allocate resources to improve resilience by acting on different indicators and attributes. The strengths are many: the proposed method is replicable, modular and expandable; it can be replicated in other contexts at different levels of detail depending on the analyst's needs: for example, at local, provincial, regional, national and macro-regional scales. It also allows for the graphical representation of specific indicators and attributes and enables the consideration and inclusion of new parameters for resilience assessment. From an analytical point of view, the calculation process does not require special resources, making the method streamlined, operational and easily usable. Possible developments of the work include the dependence of the method on the data needed; hence the importance of the quality of data and information such as (i) resource mapping, (ii) transportation graph, (iii) traffic data, (vi) availability of emergency and traffic management plans and procedures, etc.

REFERENCES

[1] Rinaldi, S.M., Peerenboom, J.P. & Kelly, T.K., Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine*, **21**(6), pp. 11–25, 2001. DOI: 10.1109/37.969131.

[2] Cohen, F., What makes critical infrastructures critical? *International Journal of Critical Infrastructure Protection*, 53–54, 2010.

[3] European Commission, Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection, 2008.
[4] Eusgeld, I., Nan, C. & Dietz, S., "System-of-systems" approach for interdependent critical infrastructures. *Reliability Engineering and System Safety*, **96**(6), pp. 679–686, 2011.
[5] Nan, C. & Sansavini, G., A quantitative method for assessing resilience of interdependent infrastructures. *Reliability Engineering and System Safety*, pp. 35–53, 2017.
[6] Hong, W., Clifton, G. & Nelson, J.D., Rail transport system vulnerability analysis and policy implementation: Past progress and future directions. *Transport Policy*, 2022. DOI: 10.1016/j.tranpol.2022.02.004.
[7] Coburn, A.W., Spence, R.J.S. & Pomonis, A., *Vulnerability and Risk Assessment*, 2nd ed., UNDP Disaster Management Training Programme, 1994.
[8] Linkov, I., Fox-Lent, C., Read, L., Allen, C.R., Arnott, J.C., Bellini, E., Woods, D., Tiered approach to resilience assessment. *Risk Analysis*, **38**(9), pp. 1772–1780, 2018.
[9] UNDRO – Office of the United Nations Disaster Relief Coordinator, Natural disasters and vulnerability analysis. Report of Expert Group Meeting, 9–12 Jul., Geneva, Switzerland, 1979.
[10] Berdica, K., An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy*, pp. 117–127, 2002.
[11] Mattsson, L. & Jenelius, E., Vulnerability and resilience of transport systems: A discussion of recent research. *Transportation Research Part A: Policy and Practice*, pp. 16–34, 2015.
[12] Borghetti, F., Petrenj, B., Trucco, P., Calabrese, V., Ponti, M. & Marchionni, G., Multi-level approach to assessing the resilience of road network infrastructure. *International Journal of Critical Infrastructures,* **17**(2), pp. 97–132, 2021.
[13] Reggiani, A., Network resilience for transport security: Some methodological considerations. *Transp. Policy*, **28**, pp. 63–68, 2013.
[14] Francis, R. & Bekera, B., A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering and System Safety*, pp. 90–103, 2014.
[15] Haimes, Y.Y., On the definition of resilience in systems. *Risk Analysis*, pp. 498–501, 2009.
[16] Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M. & Von Winterfeldt, D., A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, pp. 733–752, 2003.
[17] Carlson, L., Haffenden, J.A., Bassett, R., Buehring, G., Collins, W.J., Folga, M.S., Petit, F., Phillips, J.A., Verner, D.R. & Whitfield, R.G., *Resilience: Theory and Application*, 2012.
[18] Deublein, M., Roth, F., Willi, C., Anastassiadou, K. & Bergerhausen, U., Linking science to practice: A pragmatic approach for the assessment of measures to improve the resilience of transportation infrastructure systems. *Proceedings of the 29th European Safety and Reliability Conference*, pp. 1351–1356, 2019.